

Stirling Machine Operating Experience

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Brad Ross
Stirling Technology Company
Richland, Washington

and

James E. Dudenhoefer
Lewis Research Center
Cleveland, Ohio

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STIRLING MACHINE OPERATING EXPERIENCE

Brad A. Ross
Stirling Technology Company
Richland, Washington 99352-1698

James E. Dudenhoefer
NASA Lewis Research Center
Cleveland, Ohio 44135

ABSTRACT

Numerous Stirling machines have been built and operated, but the operating experience of these machines is not well known. It is important to examine this operating experience in detail, because it largely substantiates the claim that Stirling machines are capable of reliable and lengthy operating lives. The amount of data that exists is impressive, considering that many of the machines that have been built are developmental machines intended to show proof of concept, and are not expected to operate for lengthy periods of time. Some Stirling machines (typically free-piston machines) achieve long life through non-contact bearings, while other Stirling machines (typically kinematic) have achieved long operating lives through regular seal and bearing replacements. In addition to engine and system testing, life testing of critical components is also considered.

The record in this paper is not complete, due to the reluctance of some organizations to release operational data and because several organizations were not contacted. The authors intend to repeat this assessment in three years, hoping for even greater participation.

REMOTE POWER

Thermomechanical Generator (TMG)

The information shown in Table 1 is taken from page 188 of a book published in 1985 [1]. Three other TMGs were operated, but their operating hours are so small that they were not included in the table. All of the devices were out of service by 1985 except the

D2 machine. The diaphragms and displacer springs operated very reliably; the main sources of operational problems were the propane burners and the cooling systems.

E. H. Cooke-Yarborough, a principal investigator of the program, reported in 1990 that by the time the isotope engine, D2, was taken out of service on May 22, 1987 it had operated for 110,000 hours and 3.3×10^{10} oscillations [2]. During its life it had been topped off with helium (10% of pressure, 7 liters volume) only three times. Cooke-Yarborough has retired, but has the isotope engine (now electrically heated) in his possession along with two 120 watt propane-fired TMGs and one 60 watt TMG.

Artificial Heart Assist Engine

Stirling Technology Company (STC) staff developed a thermocompressor, designated System 4, as part of the Thermal Ventricular Assist System (TVAS). This machine featured a crank-driven displacer (the energy to drive the displacer still comes from the pressure difference across the displacer) and a pneumatic output of 3 to 5 watts. The system was operated for a relatively short time with an isotope heat source, then put on life test with an electric heater. The engine operated for a total of 60,000 hours, starting in the early 1970s. Early failures resulted from problems with the sealed ball bearings used with the displacer drive. The bearing sizes were increased, and the engine ran continuously for about 36,000 hours.

Some life testing has been performed with later systems. System 5 operated for a total of about 10,000 hours, while System 6 operated for about 20,000 hours. The System 6 life test was

Table 1. Performance of Thermomechanical Generators (significant hours)

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Application	Power (watts)		Propane Used	Efficiency		Operating Hours to April, 1983
	AC	DC	kg/year	to AC	to DC	
	Development (D) Machines					
D1 Lab	31.7		196	10.2		9,000
D2 Lab	10.7		Isotope	7.7		72,000
	Field-Trial (F) Machines					
Data Buoy F1	24.5	18.9	190	8.1	6.25	10,000
Data Buoy F2		27	166		10.7	21,000
AGA Lighthouse Up-rated	65	58	450	9.1	8.1	23,000
Total Hours:						135,000

Table 2. Bellows Life Tests at Stirling Technology Company											
Application	OD (in)	ID (in)	No. Active Convolutions	Stroke ^a (in)	Design Freq. (Hz)	Environment		Driver	Start Date	Ave. Hours ^b x10 ³	Last Inspected
						External	Internal				
Syst. 6 Drive (6) ^c	0.59	.23	20	.132	25	Air	Oil	Mech	Apr77	118	16Oct90
Syst. 6 Buffer (5) ^d	1.07	.575	17	.199	25	Oil	Air	Hyd.	Aug77	108	28Sep90
Syst. 7 Drive (4) ^e	0.42	.123	16	.120	40	Air	Oil	Mech	Sep80	88	15Oct90
Syst. 7 Buffer (4)	1.33	.93	7	.045	40	Oil	Air	Hyd.	Oct80	85	3Oct90
Syst. 7 Power (2)	0.92	.37	10	.132	40	Oil	Air	Hyd.	Oct81	72	4Oct90
Syst. 7 Actuator (5)	0.938	.344	17	.368	2	Air	Air	Mech	Apr81	83	10Oct90

^aTests performed at maximum design stroke; actual operation is at part stroke

^bTest hours through the end of 1990

^cNumber in parenthesis is the number of bellows still being tested

^d1 failure (corrosive pitting) due to sulfur attack from oil erroneously used to lubricate the drive rods

^e2 failures due to leakage; one at the 5th inside weld from mounting flange, one between 8 and 9 convolutions from mounting flange

halted due to corrosion of a magnesium poppet in one of the hydraulic valves. This material is not used with later generations, so it is not a critical issue. The poppet in question has been resurfaced and installed back into the engine; life testing of System 6 is planned to resume in mid-1991.

Probably the most critical components of the TVAS system are the metal bellows that isolate the helium working gas from the hydraulic fluid. A total of 29 bellows have been under life test at STC for the last 9 to 14 years with 26 currently under test, as shown in Table 2. The test speed is 28 to 29 Hz, which is representative of the expected operation of all of the bellows except for the blood pump actuator seal bellows, which operates at 1-2 Hz. Two types of test rigs are used that provide either hydraulic actuation or mechanical actuation. These tests are monitored daily for function, noise and oil leakage. All bellows are removed from the test rigs, inspected and helium leak tested at least annually.

SPACE APPLICATIONS

Space Power at NASA-LeRC

The NASA-Lewis Research Center (NASA-LeRC) first considered the virtues of free-piston Stirling technology for space power generation during 1976 with the introduction of the Sunpower RE-1000. NASA-LeRC tested this Free-Piston Stirling Engine (FPSE) with dashpot load to aid in the investigation of the dynamics and thermodynamics of the FPSE. The RE-1000 uses rings on the displacer and wear couples with clearance seals on the piston; it does not use non-contacting gas bearings. Since the engine ran in the vertical position, and since the engine used a dashpot load rather than a linear alternator, there were no side loads

on the piston. There was no measurable wear on the power pistons over the life of the test program; the displacer bore showed signs of wear after approximately 100 hours [3].

In 1983, under NASA Contract DEN 3-333, Mechanical Technology Inc. (MTI) began endurance testing of the EM-2 FPSE. The EM-2 was a nominal 2 kW_e machine incorporating a combustion heater, hydrostatic gas bearings, and saturated plunger type linear alternator. The power converter was operated at low-power and full-power conditions over 262 planned starts/stops. At the end of 5,385 hours, only minor scratches were discovered due to the numerous starts/stops and no debris was generated [4,5].

In 1985, under NASA Contract NAS 3-23883, MTI built and began testing of the first "high power" FPSE incorporating some of the technologies required for a space power system: 1) gas bearings and clearance seals, 2) permanent magnet linear alternator and 3) low specific mass. The machine is configured with dual-opposed pistons, each producing 12.5 kW_e [6]. In 1989, the SPDE was separated into two single-cylinder power converters, now named SPRE-I (tested at NASA-LeRC) and SPRE-II (tested at MTI). These 12.5 kW_e machines were used for component development and thermodynamic loss understanding and code development [7,8,9,10]. The test hours for all of these space power engines are listed in Table 3.

Space Cryocoolers

Cryocoolers for space applications must meet some very stringent and sometimes conflicting requirements. These requirements include cooling power at the appropriate low temperature with low input power, long lifetime, reliable and

Table 3	
ENGINE	TEST HOURS
RE-1000	280 (NASA)
EM-2	5385 (MTI)
SPDE	253 (MTI)
SPRE-I	349 (NASA), 74 (MTI)
SPRE-II	333 (MTI)

maintenance-free operation with minimum vibration and noise, compactness and light weight. Space cryocooler development activity over the last 6 years has been directed at the achievement of 5-year lifetime with a 0.95 mission success rate [11]. Table 4 lists past experience of engi-

neering development model cryocoolers that were not specifically designed for space, yet were provided space mission opportunities.

Limited lifetime of the coolers is generally attributable to loss of working fluid through elastomeric seals, wear induced degradation due to mechanical rings and seals, and contamination from material outgassing and condensing on the cold finger. Current plans for long-life cryocooler missions call for totally hermetically sealed coolers or use of gold wire seals with concomitant elimination of elastomeric seals; incorporation of non-wearing and non-touching parts via the use of clearance seals and gas bearings, magnetic bearings, or flexure bearings; and improved selection of materials (all metal construction wherever possible) and processes to minimize outgassing.

Table 4. Cumulative Past Experience of Space Flight Cryocoolers [11]			
Mission ¹	Cooler Type ²	Operating Point	Comments
RM-19 (1970) IR Telescope	{2} Malaker Integral Stirling	1.7 W at 100 K (in parallel)	Accomplished 6-month mission. Unit operated over two years before degradation and outgassing effects were observed.
SESP 71-2 Celestial Mapping Program (1971) [12]	{1} Hughes Rotary VM (2-stage)	0.15 W at 15 K, 3.5 W at 55 K	Failure of ambient cooling loop after 3 weeks; there were 690 ground hours of pre-flight testing.
SKYLAB Series (1971)	{3} Malaker Integral Stirling	77 K - 90 K, 1 W (each)	Fully successful, 10 hours operation over 90 days, many starts and stops.
P78-1 X-Ray Spectrometer (1979) [12, 13, 14]	{4} Phillips Rhombic Drive Stirling (2-stage)	0.3 W at 90 K, 1.5 W at 140 K (each) 90 K on station	Accomplished 1-year mission with 1 unit failure. Degradation and outgassing effects observed. Continued functioning through 1985.
ATMOS Atmospheric Measurement on Space Lab 3 (1985)	{2} CTI Split Stirling	1.6 W at 75 K	Reflight planned on future missions
SALYUT [15]	2-Stage Stirling with J-T	Not available	
STS 61-C (1986) [12]	{1} Cryo-dynamics Integral Stirling	1 W at 80 K	RCA IR Camera, 6-day mission
3-Color Experiment (1989)	{2} Magnavox Split Stirling	1 W at 105 K (each)	2 years to date, but contamination caused degradation after 200 hours

¹ Number in brackets [] refers to references

² Number in brackets {} refers to the number of units

Table 5. Planned Long-Life Cryocooler Missions [11]			
Mission	Cooler Baseline ¹	Operating Point	Comments
Along Track Scanning Radiometer (ATSR)	{1} Rutherford Appleton Laboratory Flexure Split Stirling	0.5 W at 60 K	Scheduled for Ariane launch in May, 1991 (ESA ERTS-1)
Improved Stratospheric & Mesospheric Sounder (ISAMS)	{2} Oxford University Atmospheric Physics Flexure Stirling	0.8 W at 80 K (each)	Scheduled for STS launch in 1991 (NASA UARS)
High Temperature Superconductivity Exp.	{2} British Aerospace Coolers with Oxford Flexure Stirling		One year mission (Air Force / NASA), 1992 Launch
X-Ray Spectrometer (XRS)	{TBD} Flexure Stirling	0.4 W at 65 K (each)	Planned for STS launch in 1996 (NASA AXAF)
Earth Observing System (EOS) Instruments	{TBD} Flexure Stirling	0.8 W at 80 K, 0.5 W at 55 K, 0.3 W at 30 K	Projected launches 1996(NASA), 1997(ESA), 1998(NASA)

¹ Number in brackets {} refers to the number of units.

Table 6. Stirling Power Systems Experience with the V-160					
Series	Time Frame	No. Built	Total Hours	Max. Single Engine Hours	Comments
A	73-77	4	2,545	1,200	Complex crankshaft seals
B	76-80	29	25,000	3,600	Introduced castings
C	78-82	26	31,000	5,300	Single Piece engine block castings
D	80-	41	149,300	25,000	Improved heating system & aux.
E	83-	24	*		3-piece engine block
F	86-	50	**		SAE flywheel/clutch plate, modular
Totals	73-	130	350,000+	25,000+	Total hours do not sum correctly

* In September, 1987, three "E" series engines demonstrated a mean-time-between failure (MTBF) of 2923 hours.

** In September, 1988, four "F" series engines had a projected MTBF of 19,000 hours [18].

All of the long life units in Table 5 use the flexure bearing demonstrated by Oxford University in the early 1980's. Flexures are used on both the compressor piston and on the displacer; linear motors drive the compressor, and in some cases control the displacer motion. STC staff has used flexural bearings at the hot end of the displacer of the long-life artificial heart engines since 1970.

North American Philips [16] is completing construction of a protoflight (used for flight qualification) Stirling cooler (5 W at 65 K) for NASA. This unit is based upon an engineering model predecessor which has been running at Philips for over 5 years except for occasional power interruptions and gas replenishment. The cooler requires sophisticated control electronics for its active magnetic bearings. Although not explicitly for space application, Philips' Eindhoven Laboratory is developing a helical hydrodynamic gas bearing for its Stirling coolers.

The Air Force is developing a baseline cryocooler for space applications. The target cooling level is 2 watts at 65 K, with a five year life goal. Two concepts are being considered: 1) a free-piston Stirling cryocooler with flexural bearings by Hughes and 2) a free-piston Stirling cryocooler with diaphragm by Creare.

TERRESTRIAL/UNDERWATER POWER

Stirling Power Systems

SPS experience was reported at the 1988 SAE conference [17], and is summarized in Table 6. At that time it was reported that the V160 was considered an "approved" standard product for the Swedish National Telephone Administration. Twenty systems were in daily use, providing up to 5 kW_e to support splicing operations. At the Dish Stirling Commercialization Workshop [19] the maximum hours on a single engine was reported to be over 28,000 hours.

United Stirling / Kockums Marine AB

Total testing time for all United Stirling engines, including the 4-95, the 4-275 and the V160 exceeds 290,000 hours, with maximum testing time for one engine exceeding 18,000 hours [20]. More than 100,000 hours of separate compo-

nent testing have been conducted to improve reliability. The 4-95 is a four cylinder kinematic Stirling engine/generator that is rated for 40 kW in automotive applications and 25 kW with helium working fluid in long-life applications such as solar power. The following information was revealed during the Dish Stirling Commercialization Workshop. Eight of these engines were tested by Southern California Edison in terrestrial solar applications in the mid-1980s. Operating time for each engine varied from 500 to 2,400 hours, with a total operational time of 12,000 hours. The solar power system availability averaged only about 50%, but most of the downtime was not due to the engine. As the control system and the auxiliaries were improved, availability increased. During a 100 day period during 1988 the system availability was 86.5%.

Kockums reported at the 1990 IECEC that 50 4-95 engines have been built [21]. These engines have accumulated 150,000 hours of operation and according to the Kockums staff 'have proved to be very reliable.' The engines are currently being adapted to 15 kW output for use in autonomous underwater vehicles [22]. Over 1000 hours of operation was obtained, then the prototype was installed in a land-based hull section.

The 4-275R SUB engine is intended to provide submarine power of nominally 75 kW, two engines are installed per submarine. The accumulated running time at sea is greater than 1000 hours per engine, with a total accumulated running time both at land and at sea of 14,000 hours [23]. The reliability is greater than expected. All failures have been corrected by the crew at sea within single hours and have not caused mission abortions. The second generation of this engine, the Mark II, will be released during 1991. The goals are improved reliability and reduced maintenance with the goal set at 2000 MTBO.

Automotive Stirling Engine

The Automotive Stirling Engine Program was initiated in 1978 under NASA contract DEN3-32. Mechanical Technology Incorporated (MTI) developed the ASE in an evolutionary manner, starting with the test and evaluation of an existing stationary kinematic Stirling engine (USAB P-40) and proceeding through two experimental engine designs—

Table 7. Accumulated Engine Test Hours			
	Engine No.	Test Hours	Uses
Mod I	1	1,013	AMC LERMA (Later Upgraded)
	2	660	Performance Development
	3	2,376	Endurance Tests
	4	238	First USA Build(Later Upgraded)
	7	4,480	Seal Life
	11	115	Performance Tests
		8,882	
Upgraded Mod I	5	3,066	Heater Head Performance, NASA TU Van
	6	4,060	820°C Endurance Test
	8	1,455	ITEP-GM, AMC Spirit
	9	1,597	ITEP-Deere, NASA TU D-150 Pickup
	10	202	Performance Tests
		10,480	
Total Mod I Test Hours		19,362	
Mod II	1	666.5	Performance Tests
	3	546.4	Development Testing
	4	19.6	Pre-LLV Characterization
	4	498.0	USPS-LLV Vehicle
Total Mod II Test Hours		1,730.5	

Table 8. Accumulated Engine/Vehicle Experience				
	Base	Mission	Hours	Miles
Upgraded Mod I Step Van	Langley, VA	Flight Line: Unleaded gasoline	527	3,554
		JP-4	536	1,882
		Diesel	165	619
	Deere & Co.	Facility Mail Delivery	175	2,437
	Total for Upgraded Mod I		1403	8,492
Upgraded Mod I Pickup Truck	Langley, VA	Flight Line	215	3,213
	Eglin, FL	Base Housing QA Inspector	282	4,667
	Randolph, TX	Base Taxi	222	4,537
	Offutt, NE	Base Supply	164	1,905
	Other		325	7,924
	Total for Upgraded Mod I		1208	22,246
Mod II Postal Vehicle (LLV)	Washington, DC	Mail Delivery	123	1,955
	Other		375	7,460
	Total for Mod II		498	9,415

the Mod I and Mod II [24]. The P-40, Mod I, Upgraded Mod I, and Mod II engines are all kinematic, 4-cylinder, Siemen's double-acting configured machines. Table 7 gives a summary of the various MTI engine builds with accumulated test hours and uses of those engines.

The NASA Technology Utilization program began in January 1986 and continued through December 1989. Structuring the program as a three-phase effort provided a gradual introduction of the technology into everyday use. Real life testing was conducted at indicated field centers and on public highways and city streets, as shown in Table 8.

TERRESTRIAL CRYOCOOLERS

Philips Cryocoolers

The cryogenic department at Philips has built and sold over 3000 Stirling cryogenerators. These have included 'whatever the prof wanted' specials, helium liquefiers, nitrogen generators and 20°K machines. The machines are kinematic with contact seals; bearing and seal replacements must be performed regularly. In late 1987 Philips reported that quite a few of their customers have been pushing their machines to run in excess of 150,000 hours [25]. A recent communication from Stirling Thermal Motors [26] indicates that mechanical overhaul of the cryocoolers used at Philips

takes place every 32,000 operating hours (approximately 3.7 years of continuous operation), and "one cryocooler installed in the lab (Philips) has already run 20 years continuously (except for maintenance), accumulating 175,000 hours."

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